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Biomass co-combustion characterization based on analysis of image sequence

Abstract. *This paper presents investigations of flame using imaging techniques obtained for different states of combustion process. Laboratory tests were carried out with different settings of secondary air flow and thermal power for different fuel mixtures that contained 10%, and 30% of biomass. Flame shape parameters as centre of gravity and area was determined for grayscale regions that were determined for each frame with Otsu's thresholding method. The mentioned parameters were accessed taking into account their potential use in combustion process diagnostics.*

Streszczenie. *Artykuł przedstawia badania płomienia z wykorzystaniem technik wizyjnych dla różnych stanów procesu spalania. Testy laboratoryjne zostały przeprowadzone przy różnych ustawieniach przepływu powietrza drugiego i mocy dla mieszanin paliwa zawierającego 10% i 30% biomasy. Parametry obszaru płomienia jak środek ciężkości i pole powierzchni poddane ocenie pod względem ich potencjalnego wykorzystanie w diagnostyce procesu spalania. (**Charakteryzowanie procesu współspalania biomasy z wykorzystaniem sekwencji obrazu**).*

Keywords: biomass co-combustion, processes diagnosis, image processing.
Słowa kluczowe: współspalanie biomasy, diagnostyka procesu, przetwarzanie obrazu.

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Introduction

The European Union have expressed that policy by endorsement a firm commitment of individual countries to reduce greenhouse gases by at least 20% by 2020, in comparison with the 1990 level. The package, known as "3x20", includes CO_2 emissions reduction by 20%, energy consumption drop by 20% and increase in the renewable energy share the EU up to 20% (from the current 8.5%) by the year 2020. Achieving these objectives of the climate and energy package requires development and implementation of low carbon technologies.

Co-firing of coal and biomass is inexpensive and one the easiest way of use renewable energy source for the existing combustion facilities could be applied after some adaptations. Biomass-coal co-combustion can be quickly adapted in large-scale systems. Combustion process is stabilized by presence of coal in fuel mixture. On the other side, biomass-coal co-firing has significant drawbacks [1, 2]. Biomass contain less carbon and more oxygen comparing to coal that results in lower heating value. Higher chlorine contents rise corrosion rate. The melting point of the ash can be low. It causes increased slagging and fouling of combustor surfaces that reduce heat transfer and result in corrosion and erosion problems. Comparing to coal, biomass has lower density and friability that results in possible stratification of fuel mixture contents during its conveyance to burners. Higher moisture content as well as ash can result in possible combustion stability problem [2, 3]. What is more, both physical and chemical biomass parameters of biomass are unsteady in time. Thus, combustion process is difficult to lead and a proper monitoring system is essential to ensure proper operational conditions taking into consideration stability issue of the process, individually for each burner.

Reaction zone is potentially the quickest source of information of a combustion process for it is usually a source of radiation. Thus, optical sensing methods conjoined with advanced signal analysis allow non-intrusive characterization of combustion process, that can be held in real-time [4, 5].

The measurable physical attributes of flame, such as for example shape of luminous area, flicker frequency provide vital information of combustion process and is reported to use both in laboratory and full-scale facilities [4, 5].

The mentioned above approach was applied in several combustion tests of coal-biomass mixtures at different air contents and values of thermal power. Analysis of flame images allows to determine various parameters of flame such as geometric (e.g. size, position), radiation properties (e.g. emission spectrum, irradiation distribution) [5].

Experiment

Combustion tests were done in a 0.5 MW_{th} (megawatt of thermal) research facility, enabling scaled down (10:1) combustion conditions. The main part is a cylindrical combustion chamber of 0.7 m in diameter and 2.5 m long. A swirl burner about 0.1 m in diameter is mounted horizontally at the front wall. The stand is equipped with all the necessary supply systems: primary and secondary air, coal, and oil. Pulverized coal for combustion is prepared in advance and dumped into the coal feeder bunker. Biomass in a form of straw is mixed with coal after passing through the feeder.

The combustion chamber has several inspection openings on both sides. Flame images were transferred from the inside of the combustion chamber through a 0.7m borescope, that was placed in one of the inspection openings and attached to high-speed CMOS camera as shown in fig. 1. The optical system was cooled with water jacket. Additionally, purging air was used to avoid dustiness of optical parts.

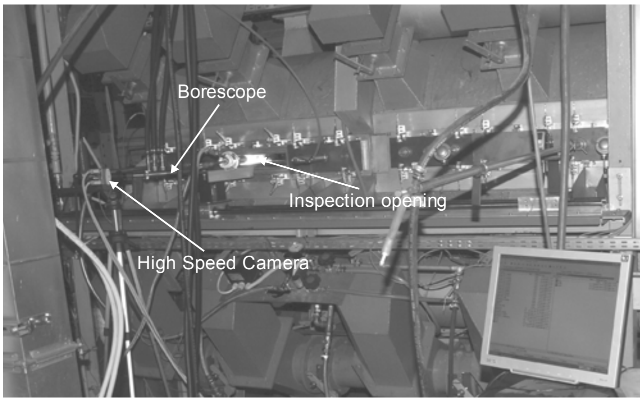


Fig.1. Laboratory combustion facility

The way of camera mounting has enabled to observe only part of flame that was placed close to burner nozzle, in spite of relatively large numerical aperture of the borescope.

Previous researches with fibre-optic, multichannel flame monitoring system have shown, that this is the most sensitive flame region to changes of input parameters of the burner [6].

Combustion testes were done for nine different settings of the combustion facility, where thermal power (P_{th}) and excess air coefficient (*lambda*) were kept constant and set independently for known biomass content. *lambda* is defined as a quotient the mass of air to combust 1kg of fuel to mass of stoichiometric air. Thermal power that was released inside the combustion chamber was regulated by adjusting fuel flow rate knowing heating value of the fuel mixture. The exact values of thermal power and excess air coefficient are collected in Table 1.

Table 1. Settings of combustion facility during biomass-coal co-combustion tests

Test #	1	2	3	4	5	6
P_{th} (kW)	250	250	250	300	300	300
lambda	0.75	0.65	0.85	0.75	0.65	0.85
Test #	7	8	9			
P_{th} (kW)	400	400	400			
lambda	0.75	0.65	0.85			

The tests were performed for two fuel mixtures containing 10% and 30% of biomass (straw) respectively. During the combustion tests, physical properties of biomass (particle size, inherent moisture, etc.) remained unchanged as well as the all image acquisition settings, such as camera gain, frame rate, exposure time.

Data processing and results

For coal and coal-biomass flames the dominate mechanism of radiation generation is thermal radiation emitted by solid particles [7], apart from radiation emitted by hot gases and chemiluminescence. Assuming the luminous particles are grey body spectral distribution of the radiation emitted by flame can be determined according to Planck's law:

$$u(\lambda,T)=\varepsilon(\lambda)\frac{2hc^2}{\lambda^5}\cdot\left(e^{\frac{hc}{\lambda kT}-1}\right)^{-1}, \tag{1}$$

where: $u(\lambda,T)$ – irradiance for a given wavelength λ and temperature T, $\varepsilon(\lambda)$ - emissivity, h – the Planck constant, c – the speed of light, k – the Boltzmann constant. Temperature inside the combustion chamber was equal to about 1200°C. Spectral power distribution of blackbody at temperatures equal to 1000°C and 1300°C is shown in Fig. 2

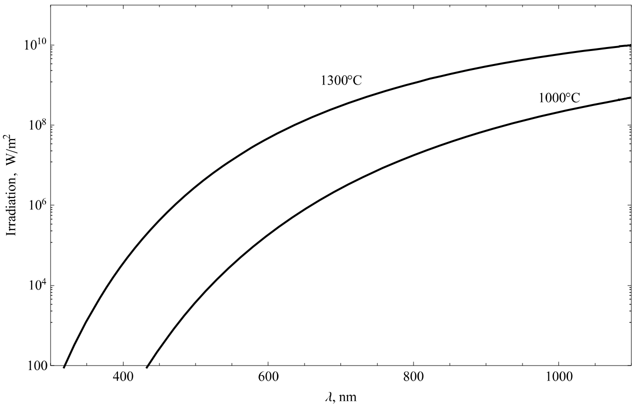
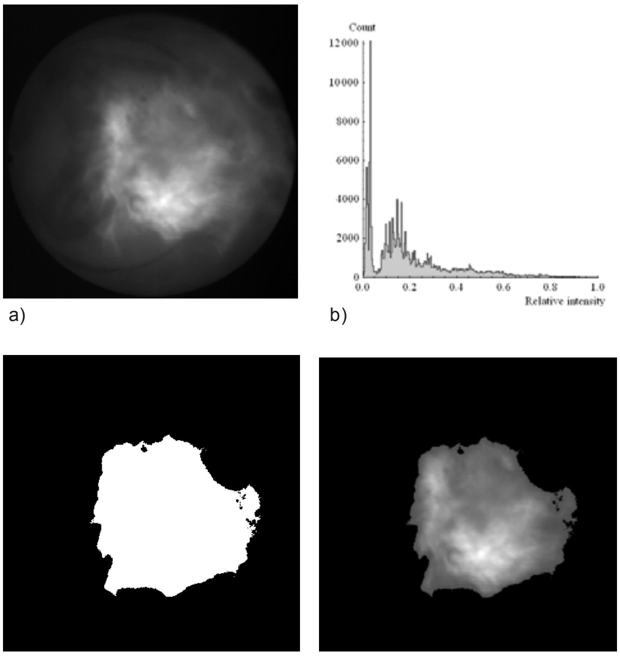


Fig.2. Spectral power distribution of blackbody for temperatures of coal flame

Colour images of flame were captured for mentioned above variants using a camera with Bayer filter (RGB). It can be easily pointed out that in the case of flame images being discussed radiation intensity corresponding to blue and green components of colour image is a few orders of magnitude lower than that of red. For that reason the red component was only applied in determination of flame area rather than luminance that is affected by noisy green and blue components. Thus, images containing only red component was further processed as grayscale objects.

Within each frame of the acquired image sequence flame region was determined regarding pixel amplitude. Such an assumption was possible to accept for flame was the only luminous object within field of view of the borescope applied, as depicted in Fig 3a. Histogram of an example frame was presented in Fig 3b. The flame region was determined using Otsu's global thresholding method, that is efficient especially when image histogram is bimodal [8], as it does in the case investigated. Greyscale flame region was obtained as subtraction of a given image frame and the negative of flame region obtained by Otsu's method and is shown in Fig. 3d.



a) b)

c) d)

Fig.3. a) The red (RGB) component of an example frame, b) histogram obtained, c) flame region extracted with Otsu's method, d) greyscale flame area being investigated

The flame region greyscale area was calculated according to the following formula:

$$Area\ grey=\sum_{x,y\in A}g(x,y), \tag{2}$$

where $g(x,y)$ – luminosity of a grey pixel at coordinates x, y. Greyscale flame region center of gravity is defined by the first two normalized moments of $g(x,y)$ i.e., by (m_{10}, m_{01}), where

$$m_{p,q}=\frac{1}{Area\ grey}\sum_{x,y\in A}x^p y^q g(x,y). \tag{3}$$

Changes of greyscale flame area that were obtained for fuel mixtures with 10% and 30% content of biomass obtained for nine different values of P_{th} and *lambda* (defined in Table 1). Example results are presented in Fig.4.

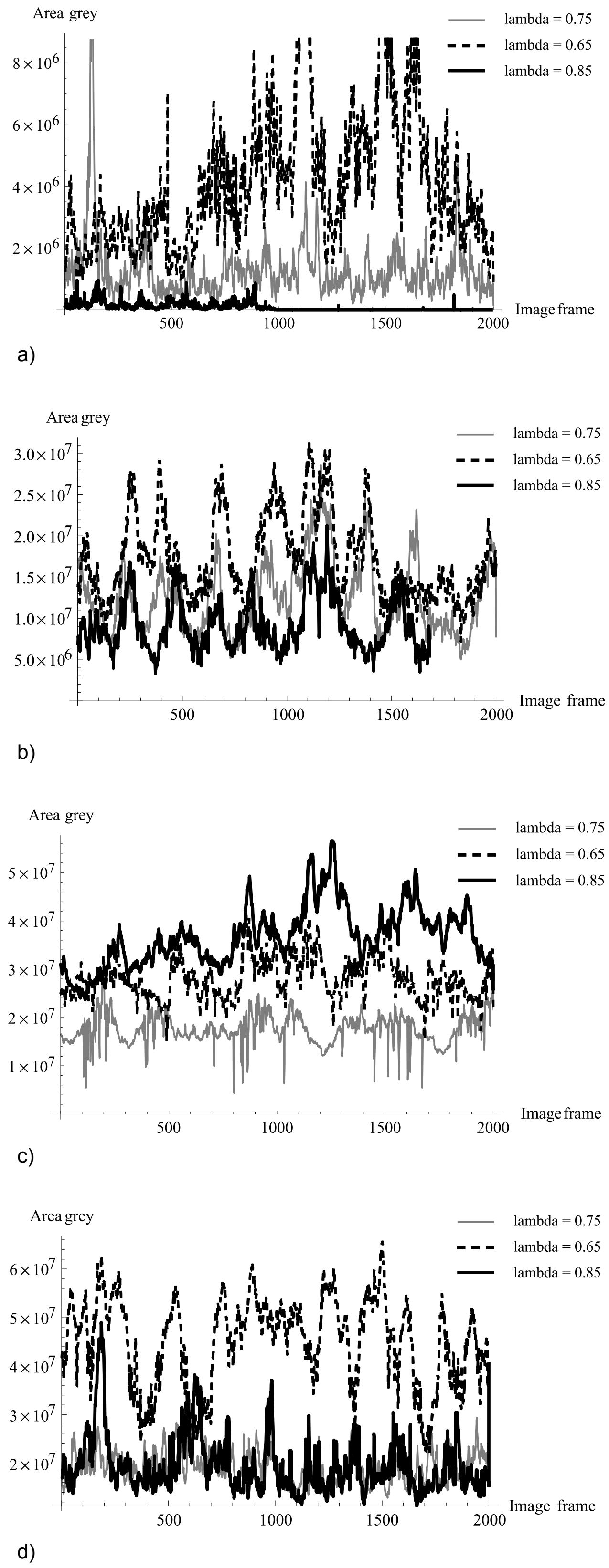


Fig.4. Greyscale flame area obtained for the examined states of biomass co-combustion process: a) 30% straw, P = 250kW; b) 10%straw, P = 250kW; c) 30% straw, P = 250kW; d) P = 400kW, 10% straw, P = 400kW

In order to find general dependences between flame image parameters and combustion process states being analysed, mean values of grayscale flame area as well as coordinates of centre of gravity were calculated for all settings of combustion facility and are shown in Fig.5 and Fig.6, respectively.

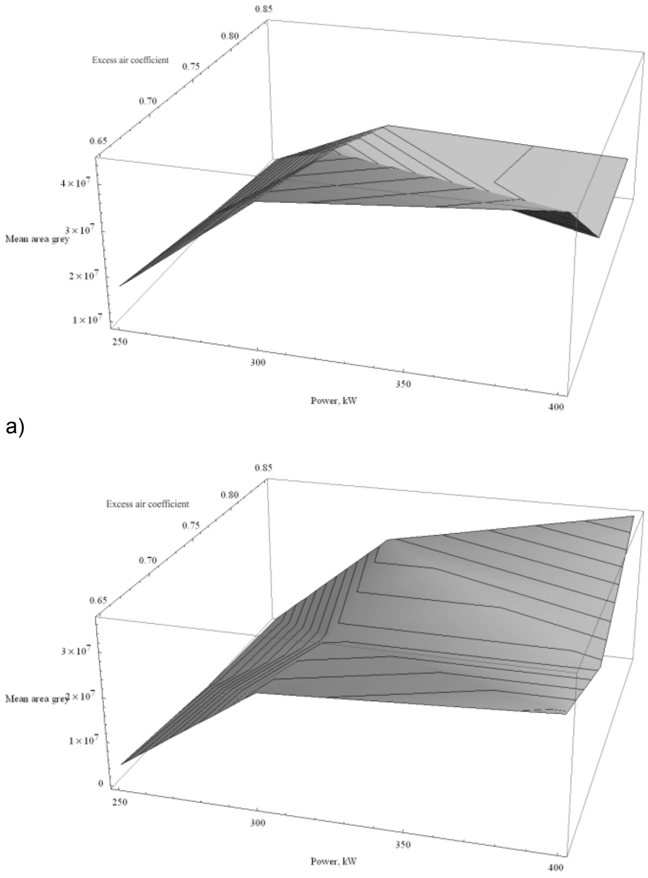
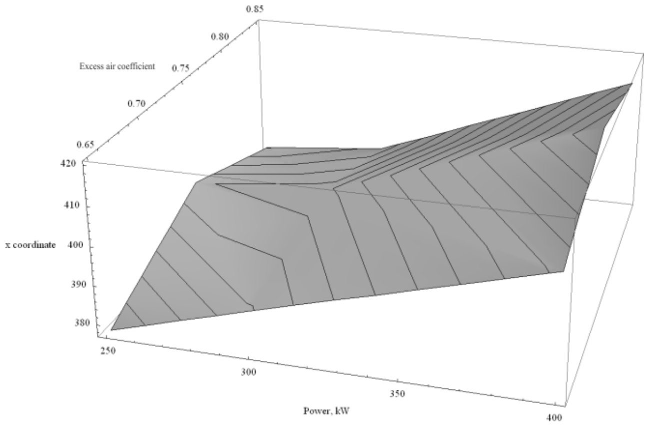
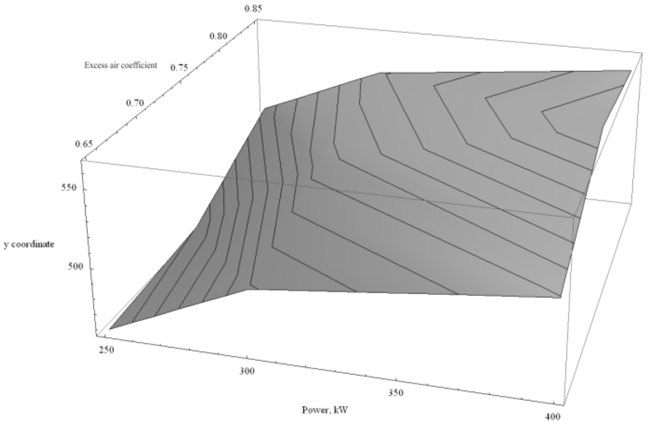


Fig.5. Mean value of greyscale flame area obtained for the examined states of biomass co-combustion process: a) fuel mixture with 10% straw, b) fuel mixture with 30% straw

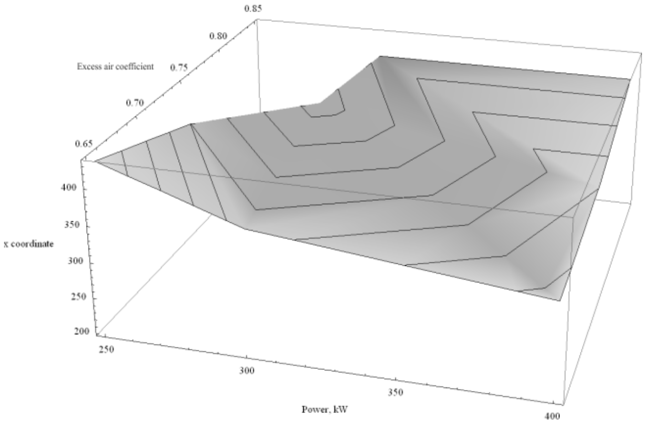
Magnitude of flame area is connected with amount of fuel that is delivered to the burner. The more fuel stream, the more heat power is released and the greater flame area observed. As it can be observed in Fig. 5, greyscale flame area monotonic dependence on thermal power of the facility for a fixed excess air coefficient, except the case when fuel mixture contains 10% of biomass and *lambda* is 0.75.



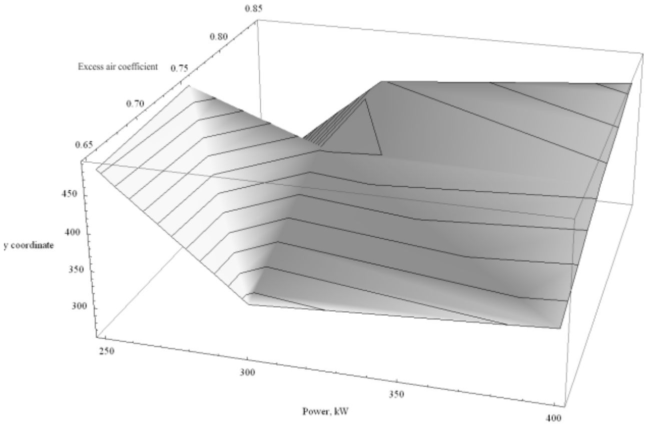
10% straw



10% straw



30% straw



30% straw

Fig.6. Coordinates of greyscale flame region centre of gravity obtained for the examined states of biomass co-combustion process: fuel mixture with 10% straw, fuel mixture with 30% straw

Discussion

Fuel mixtures with biomass added generally ensured stable operation. However in the case of 30% content of biomass, P_{th} = 250kW, *lambda* = 0.85 flameout has been observed as shown in Fig. 4a. The combustion process was sustained by supplementary gas burner.

Generally, increasing thermal power of the facility results in increasing greyscale flame area as shown in Fig. 5, both for 10% and 30% biomass mixtures. However changes of *lambda* values have different influence on greyscale flame area. For fuel mixtures with 10% of biomass added rise of *lambda* correspond to drop of area values, whereas for 30% fuel mixtures it has the reverse effect.

Greyscale flame region center of gravity tends to shift for 10% fuel mixtures on one direction as P_{th} and excess air coefficient are changing. It cannot be observed for 30% mixtures, where no dependence on the discussed parameters can be found.

Conclusions

It can be observed that it is hard to distinguish combustion process states taking into consideration greyscale flame area as well as its center of gravity obtained from single frame, hence analyzing sequence of images is necessary. it is possible to find some generalizations especially for fuels with lower biomass contents. It would be useful in controlling the combustion process.

It should be underlined that the factors being investigated strongly depend on burner type and size of combustion chamber and it why they cannot be used directly in full scale combustion facilities.

REFERENCES

[1] Sami M., Annamalai K., Wooldridge M, Co-firing of coal and biomass fuel blends, *Progress in Energy and Combustion Science*, 27 (2001), 171-214
[2] Pronobis M., The influence of biomass co-combustion on boiler fouling and efficiency, *Fuel*, 85 (2006), No 4, 474-480
[3] Lu G. et al., Impact of co-firing coal and biomass on flame, *Fuel*, 87 (2008), 1133-1140
[4] Lu G., Gilbert G., Yan Y., Vision based monitoring and characterization of combustion flames, *Journal of Physics: Conference Series*, 15 (2005), 194–200
[5] Marques J.S., Jorge M.P., Visual inspection of a combustion process in a thermoelectric plant, *Signal Processing*, 80, (2000), 1577-1589
[6] Wójcik W., Światłowodowy układ do monitorowania procesu spalania, *Pomiary Automatyka Kontrola*, 53 (2007), nr 11, 24-28
[7] Lou C., Zhou H., Yu P.Z., Measurements of the flame emissivity and radiative properties of particulate medium in pulverized-coal-fired boiler furnaces by image processing of visible radiation, *Proceedings of the Combustion Institute*, (2007) No. 31, 2771–2778
[8] Otsu N., A Threshold Selection Method from Gray-Level Histograms, IEEE Transactions on Systems, Man and Cybernetics, SMC-9 (1979), No.1, 62-66

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